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NIST Technical Note 1426

The Fujita Tornado Intensity Scale: A Critique Based on Observations of the Jarrell Tornado of May 27, 1997

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Abstract

On May 27, 1997, several tornadoes hit the Central Texas area in the counties of McLennan, Bell, Williamson, and Travis. The most destructive of these tornadoes swept through a housing area on the outskirts of Jarrell, Texas. Jarrell is a Central Texas town with a population of 410 located approximately 60 km north of Austin, Texas. The Jarrell tornado destroyed about 40 single-family residences and other structures, killing 27 people. A post-storm damage survey was made at Jarrell by a team coordinated by the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM). We report damage observations and conclude on their basis that the worst damage can be explained by wind speeds corresponding to an F3 rating on the Fujita tornado intensity scale (wind speeds of 71 m/s to 92 m/s). An F4 (93 m/s to 116 m/s) rating, or the F5 (117 m/s to 142 m/s) rating officially issued by the National Weather Service (NWS), need not be assumed to explain that damage. We ascribe the NWS rating to the failure of the Fujita tornado intensity scale to account explicitly for the dependence of wind speeds causing specified types of damage or destruction upon the following two structural engineering factors: (1) quality of construction, defined as degree of conformity to applicable standards requirements, and (2) the basic design wind speed at the geographical location of interest.

Keywords: Building technology; Fujita intensity scale; meteorology; structural engineering; tornadoes; wind engineering; wind speeds.

THE FUJITA TORNADO INTENSITY SCALE: A CRITIQUE BASED ON OBSERVATIONS OF THE JARRELL TORNADO OF MAY 27, 1997

1. Introduction

On May 27, 1997, tornadoes hit the Central Texas area in the counties of McLennan, Bell, Williamson and Travis. The most destructive of these tornadoes swept through a housing area on the outskirts of Jarrell, Texas, a Central Texas town with a population of 410 located approximately 60 km north of Austin, Texas. The tornado destroyed about 40 single family residences and other structures, killing 27 people, and subsequently was rated by the National Weather Service (NWS) as a category F5 tornado (called *Incredible Tornado* on the Fujita tornado intensity scale, wind speeds range from 117 m/s to 142 m/s (261 mph to 318 mph), see Appendix 1) based on early visual observations of the damage. A post-storm damage survey was made at Jarrell by a team coordinated by the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM), National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce. The findings of the damage survey are presented in this report.

1.1 Report Objectives

The purpose of this report is to:

- summarize main observations of damage caused by the Jarrell tornado;
- use structural engineering considerations in support of our assessment that the damage caused by the Jarrell tornado may be explained by wind speeds corresponding to an F3 rating on the Fujita tornado intensity scale (71 m/s to 92 m/s (158 mph to 206 mph)), see Appendix 1). An F4 rating, the F5 rating (associated with the descriptor "incredible tornado") officially issued by the NWS need not be assumed to explain that damage;
- note that the classification of the Jarrell tornado proposed by NWS' meteorologists on the basis of their use of the Fujita intensity scale was F5 (Alexander, 1997), which corresponds to wind speeds of 117 m/s to 142 m/s (261 mph to 318 mph), and explain why this latter assessment is due, in our opinion, to two shortcomings of the Fujita tornado intensity scale; and
- suggest possible changes in the approach to the formulation of that scale which would enable meteorologists and other professionals to make more realistic assessments of tornado wind speeds than the Fujita intensity scale currently allows.

1.2 Post-storm Survey

The OFCM team members included Long T. Phan, a research structural engineer of the National Institute of Standards and Technology in Gaithersburg, Maryland (Structures Division, Building and Fire Research Laboratory), and Brian E. Peters, a warning coordination meteorologist of the National Weather Service in Alabaster, Alabama. The team conducted ground surveys and two aerial surveys of the areas affected by the tornadoes. The aerial surveys were supported by the Texas Wing Civil Air Patrol Station in Waco. The ground surveys were conducted on May 29 and June 1, 1997. The first aerial survey was conducted on May 30, 1997 using a fixed wing aircraft flying between 760 m and 910 m (2500 ft to 3000 ft). The second aerial survey was conducted on May 31, 1997, using a helicopter flying between 150 m and 300 m (500 ft to 1000 ft).

The OFCM survey covered the damage sites by all tornadoes that hit the central Texas region on May 27, 1997. The purpose of the survey was to document the tornado ground tracks, including beginning and end points, path lengths, maximum widths, and the associated structural damage. The spatial information was obtained by using a commercial Global Positioning System (GPS) and mapping software with an accuracy of ±90 m (±300 ft). Coordinates of the beginning and end points of a tornado track as well as damage locations on each track were recorded by flying directly over the points of interest and recording their coordinates using the GPS. These coordinates were then overlaid onto the map of the affected regions to form the tornado path and allow an estimate of the tornado lengths and widths. Structural damage information was gathered by aerial and ground inspection of the damage sites.

2. Synoptic Weather Conditions

The following information was compiled from reports published by NWS (The Jarrell/Cedar Park and Pedernales Valley Tornadoes -- Summary of Weather Event of May 27, 1997) and the National Oceanic and Atmospheric Administration (NOAA GOES-8 Satellite Soundings Analysis of Jarrell, Texas Tornado Event - 5/27/97) on their respective web sites.

During the afternoon of May 27, 1997, a system of severe thunderstorms developed over central and south central Texas. The NWS' summary of the weather event of May 27, 1997 (updated 6/02/97) described extremely unstable conditions as an upper level weather system moved over Texas from the west. At the surface, a cool front moving south was intersected by an outflow boundary from a thunderstorm system moving southwest in central Texas and also by warm and humid southerly winds from the south and southeast. Dew points in this part of Texas were in mid- to upper 20s (°C). The explosive growth of this weather system was captured over a 6 hour interval, between 3:45 P.M. (CDT) and 9:45 P.M. (CDT) by the NOAA Storm Prediction Center (SPC) infrared (IR) satellite imagery.

At 12:54 P.M. (CDT) May 27, 1997, the SPC in Norman, Oklahoma issued Tornado Watch 338, effective from 1:15 P.M. (CDT), indicating that the occurrence of tornadoes, hail up to 90 mm (3.5 in) in diameter, thunderstorm wind gusts up to 36 m/s (80 mph), and dangerous lightning was possible in the watch areas from East Texas to western Louisiana. The city of Jarrell was in this watch area (see fig. 1).

At 3:30 P.M. (CDT) the same day, the NWS in Austin/San Antonio issued a Tornado Warning effective until 4:30 P.M. (CDT) for south central Texas and Williamson County (of which Jarrell is a part). The NWS Tornado Warning indicated that:

> *At 3:25 P.M. a tornadic thunderstorm was located about 8 km west of Jarrell moving southeast at 1.6 km/hr. This type of storm has a history of producing tornadoes and large hail. The city of Jarrell is in the path of this storm.*

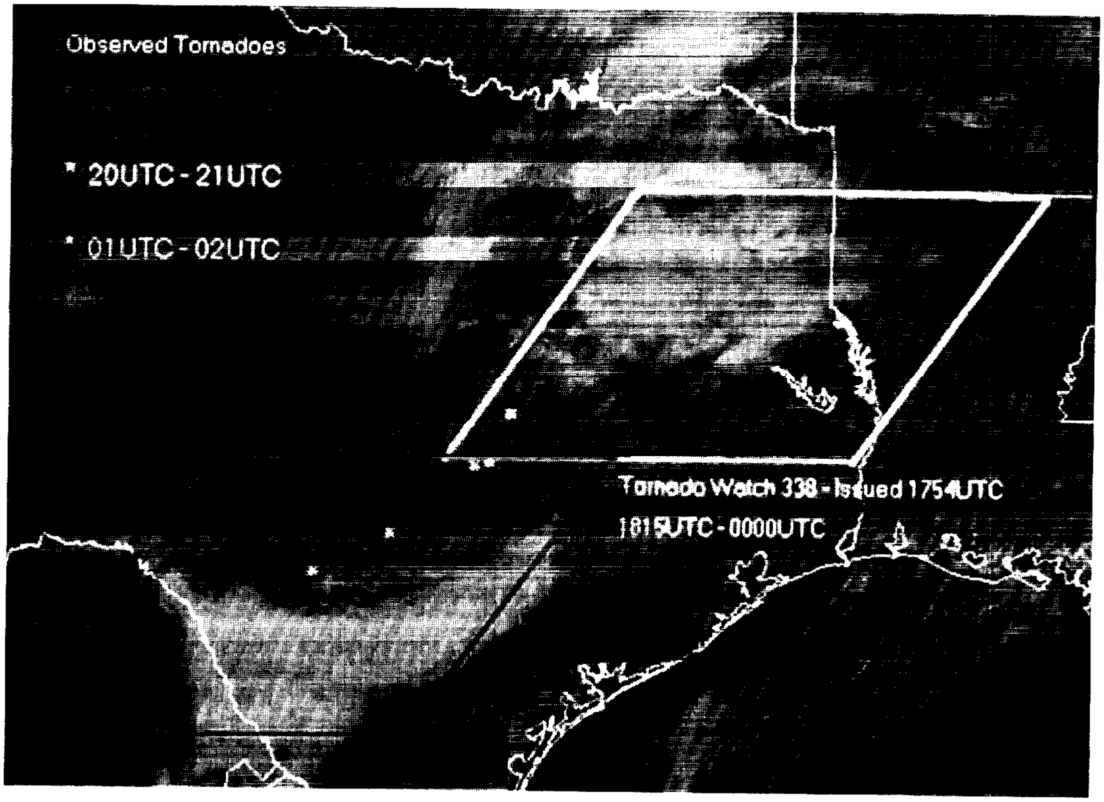

Figure 1. NOAA GOES-8 satellite image of Central Texas and tornado watch areas 338 (right box) and 340 (left box), respectively (image taken at 11:15 A.M., CDT).

Shortly before 3:40 P.M. (CDT), tornado sirens were sounded alerting residents in Jarrell of tornado sightings. Shortly before 3:45 P.M. (CDT), the most violent of all tornadoes that were spawned on May 27, 1997, now known as the Jarrell tornado, first struck areas of Bell County and then crossed into Williamson County. The city of Jarrell suffered 27 confirmed deaths and more than 40 structures were destroyed, including single-family homes, a commercial light steel frame structure, and several mobile homes. Most of the deaths and structural damage occurred in Jarrell's Double Creek Estates subdivision. Images of the thunderstorm that produced this tornado were captured by the NOAA GOES-8 satellite and the Austin, Texas WSR-88D radar site (see figs. 2a and 2b).

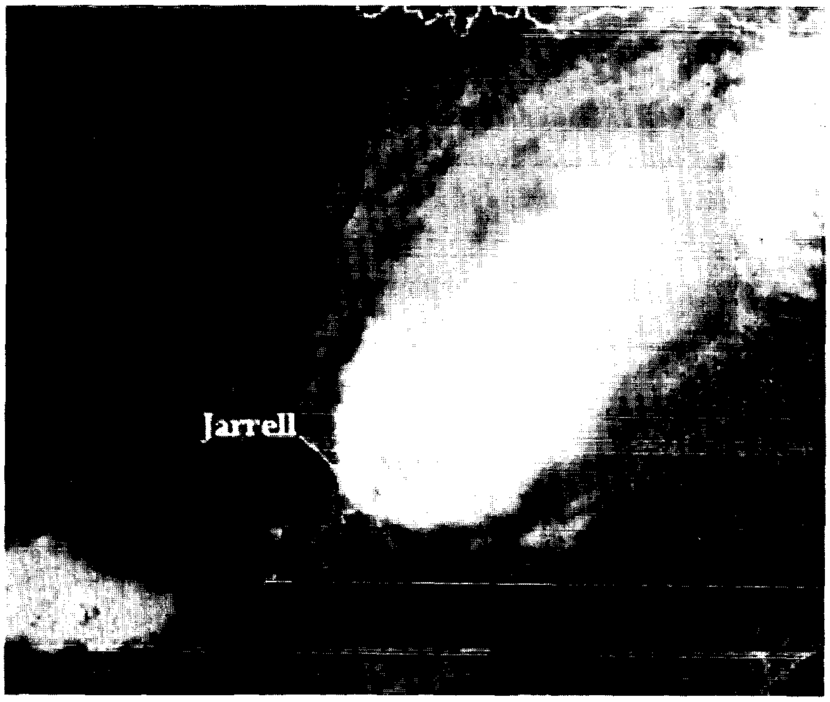

Figure 2a. GOES-8 satellite image of the thunderstorm that produced the Jarrell tornado (picture from NOAA SPC website).

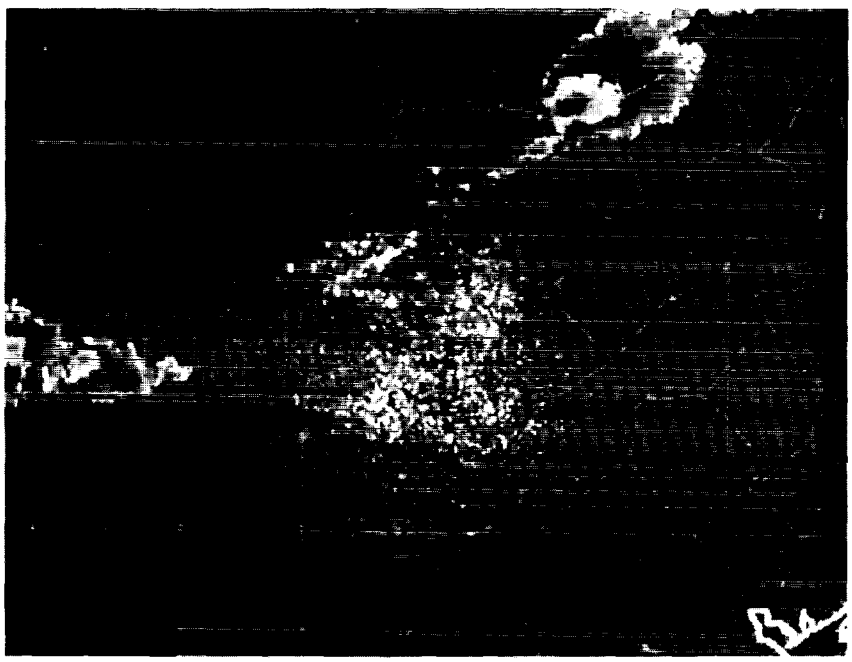

Figure 2b. Radar reflectivity image of the thunderstorm that produced the Jarrell tornado (picture from NOAA SPC web site).

3. Jarrell Tornado

3.1 Tornado Path

Figure 3 shows the path of the Jarrell tornado, based on information obtained in the OFCM damage survey. The path began in Bell County at a point about 1.3 km northwest of the Prairie Dell exit from Interstate 35 (coordinates 30° 53.90' N/97° 35.20' W). The tornado tracked southwestward, almost parallel to Interstate 35, then crossed the Bell/Williamson County line where it assumed a more westerly course. The tornado path ended in a heavily wooded area southwest of Jarrell in Williamson County (coordinates 30° 49.18' N/97° 40.12' W). Based on the information from the GPS, the path length of the tornado was estimated to be 12.2 km (7.6 mi), of which 3.9 km (2.4 mi) was in Bell County and 8.3 km (5.2 mi) was in Williamson County. The Double Creek Estates subdivision was located in open terrain, slightly rolling, with few trees. The tornado's maximum path width was measured in that subdivision to be approximately 1.2 km (0.75 mi). Witnesses estimated that its translational speed was between 8 km/hr and 16 km/hr (5 mph to 10 mph).

Figure 3. Jarrell tornado path.

3.2 Main Observations of Damage Caused by the Jarrell Tornado

Damage began in open terrain in Bell County and was limited primarily to trees and the roofs of a few residential structures (see fig. 4). The tornado then crossed the Bell/Williamson County line and moved across County Road (CR) 308, CR 305, and CR 307. The locations where the tornado crossed these roadways were clearly marked by strips of scoured asphalt road surface (see fig. 5), typically as wide as the road and with lengths of 1.5 m (5 ft) to more than 100 m (330 ft). The top layer of the asphalt pavement was approximately 20 mm (0.8 in) thick. We ascribe the scouring of the asphalt to differences between the atmospheric pressure of pockets of air trapped underneath the asphalt and the lower atmospheric pressure at the center of the tornado.

Figure 4. Damage to roof of residences in Bell County at the beginning of the Jarrell tornado track.

Figure 5. Scoured asphalt road surface in the vicinity of Double Creek Estates subdivision.

The next structural damage along the tornado path occurred at the corner of CR 305 and CR 307 in Williamson County, where a culvert plant collapsed (figs. 6 to 8). The plant was of light steel frame construction with non-reinforced masonry and steel tube columns supporting steel pipe, gable roof trusses. The steel tube columns were cast into a concrete mat foundation on grade. The roofing, supported by wood purlins, consisted of corrugated sheet metal. An identical plant approximately 15 m (50 ft) away from the collapsed culvert plant, and other surrounding structures, suffered only minimal damage (fig. 8). A mobile home used as an office was hit by a conventional "two by four" timber member 1.2 m (4 ft) long, but the missile did not penetrate into the home. A mobile home located about 150 m (500 ft) north-northwest of the plant had only minor damage. Its occupants fled to a house that was in the center of the damage path, where they were reportedly killed.

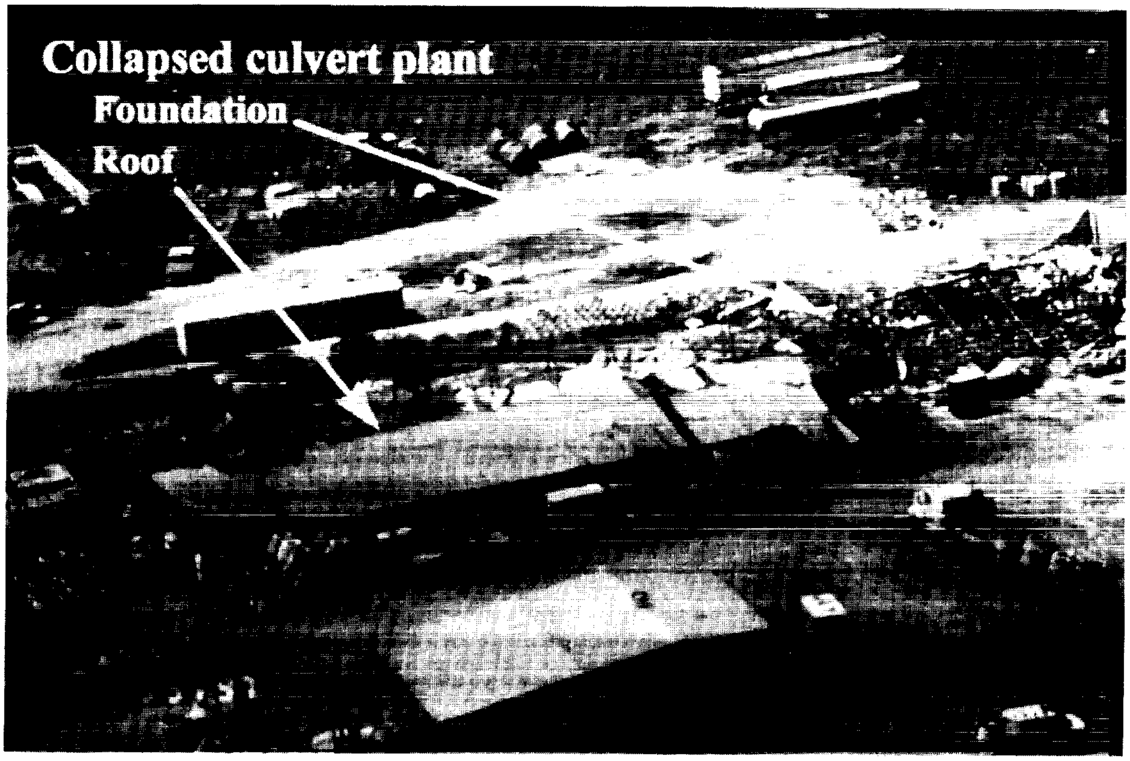

Figure 6. Aerial view of collapsed culvert plant.

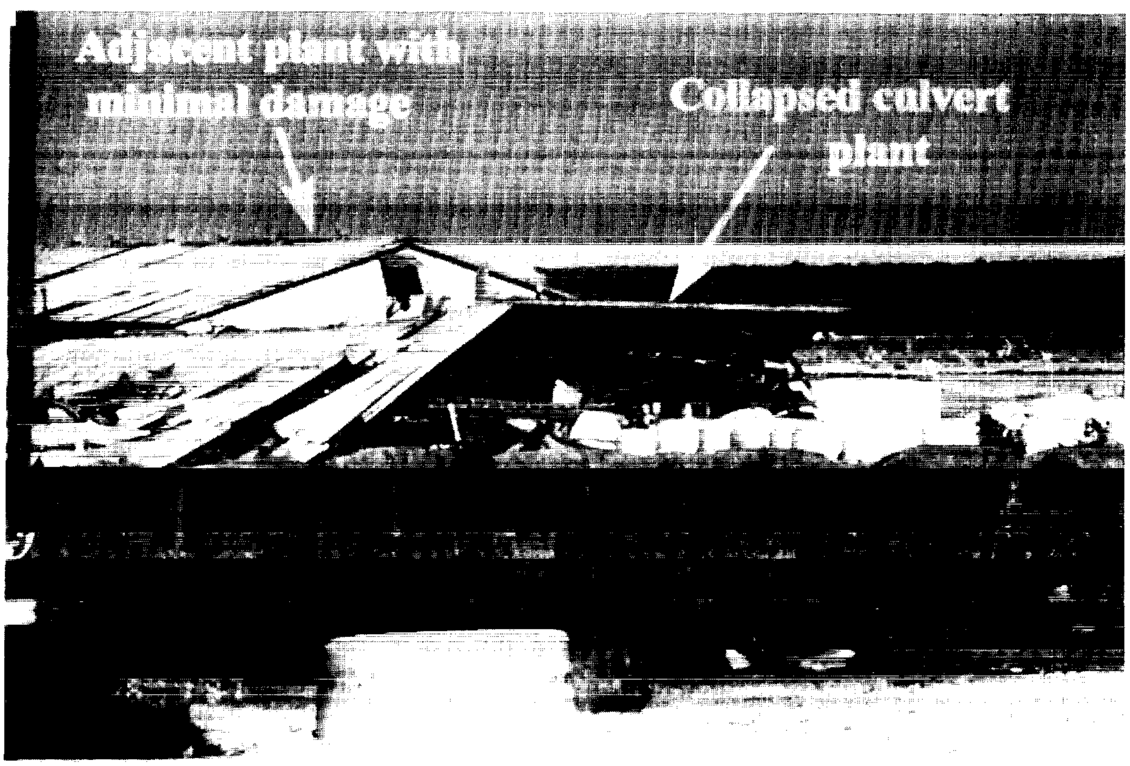

Figure 7. Ground view of collapsed culvert plant.

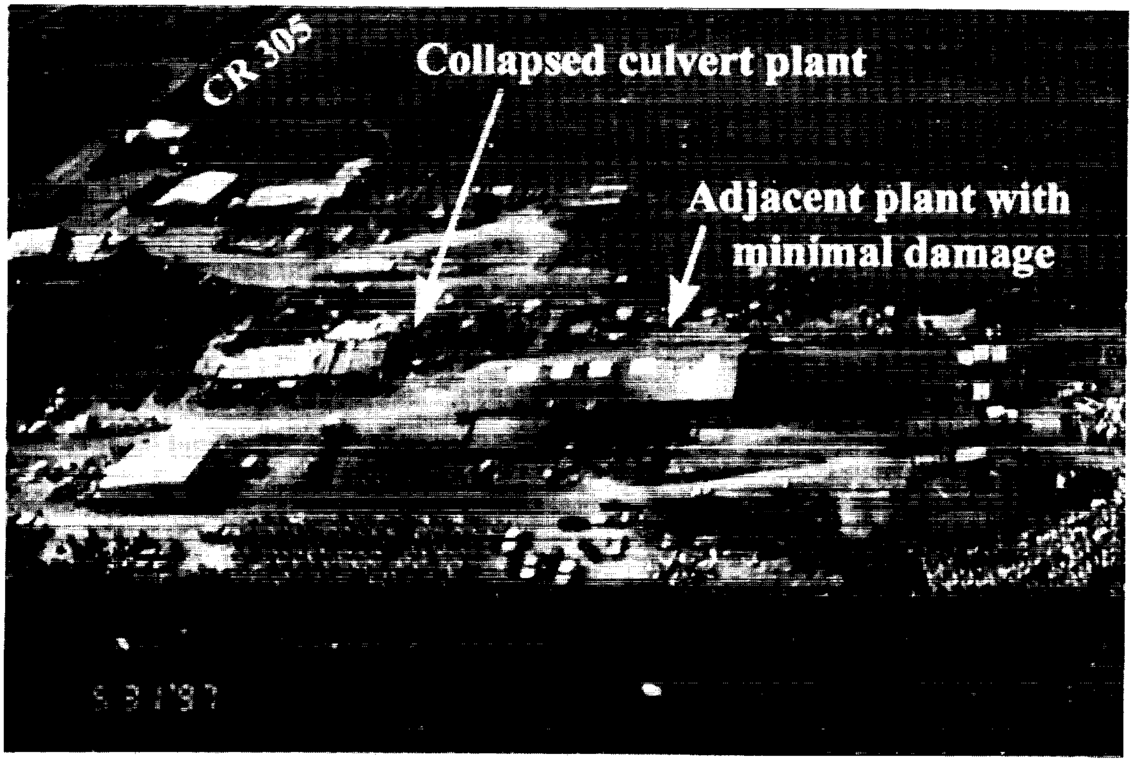

Figure 8. Aerial view of entire culvert plant complex.

As the tornado continued its track south southwestward, a barn located just southwest of the culvert plant and just north of the Double Creek Estates subdivision was destroyed (fig. 9). The tornado then moved through the Double Creek Estates subdivision and the surrounding areas, where the destructive path widened to its maximum of 1.2 km (0.75 mi) and the tornado became most deadly.

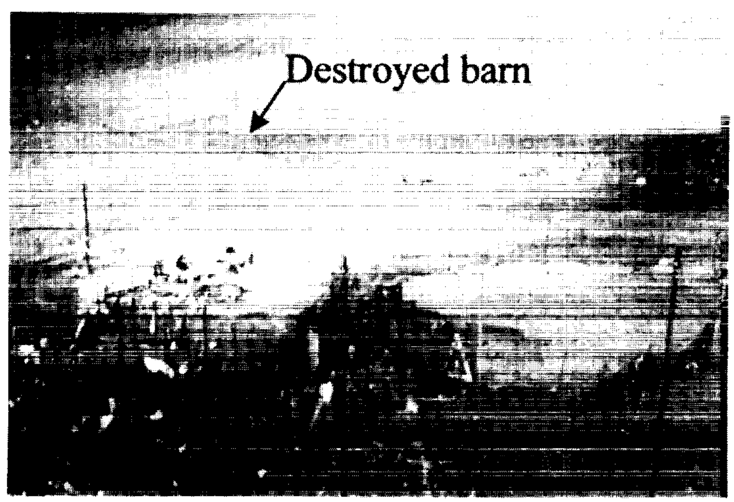

Figure 9. Destroyed barn located between culvert plant complex and Double Creek Estates subdivision.

Figure 10 shows a portion of the Double Creek Estates subdivision after the tornado passage. The structures in the subdivision consisted mainly of single-family residences built over the last 15 years or so, of the typical slab-on-grade construction type. Owing to the presence of limestone bedrock close to the surface, most houses had no basements or underground shelters. The houses, which consisted mainly of wood frame construction, were completely swept off the concrete foundations. The debris of the houses were so small and scattered that it was difficult to spot them from the air.

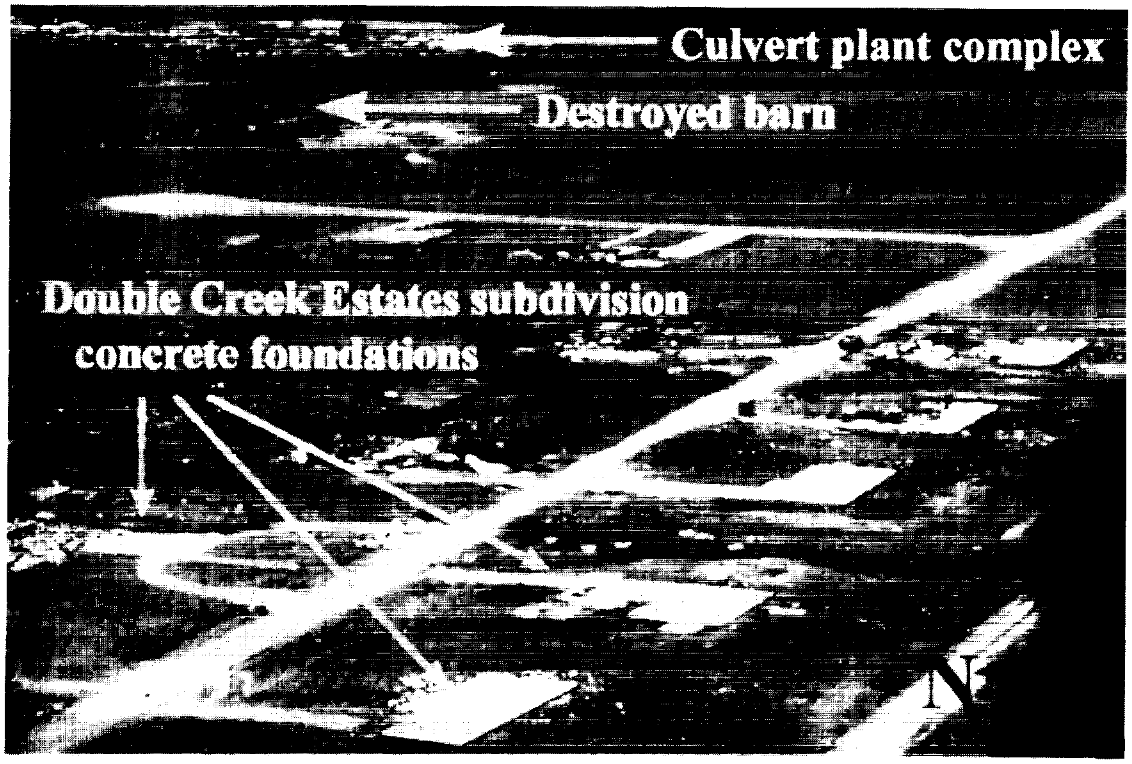

Figure 10. Aerial view of portion of the Double Creek Estates subdivision.

Inspections of the concrete slab-on-grade foundations performed during the ground surveys revealed that, in many cases, even the sill plates that connected the wood frames to the concrete foundations were blown away (see fig. 11). This suggests that the connections between the sill plates and the foundations were not as strong as those between the sill plate and the wood frames. Random, close examination of a few concrete foundations suggested that the houses in this subdivision may not have been well built. For some houses, there was evidence that the sill plates had been connected to the foundations by nails. Figure 12 shows a nail that remained in the foundation, but pulled through the sill plate. Figure 13 shows examples where the nails, which appeared to have been spaced 0.9 m (3 ft) apart, pulled out of the foundation. There was no evidence of anchor bolts or steel straps used at the few random foundations where close inspections were performed. We note that the Council of American Building Officials (CABO) One and Two-Family Dwelling Code (1995) requires that sill plates of exterior walls for wood-frame construction be anchored to the concrete foundation by 13 mm-diameter (1/2-inch) anchor bolts not more than 1.83 m apart and less than 0.31 m from corners. We also note that Williamson County has not adopted a building code, even though Jarrell had been hit by a tornado on May 17, 1987.

The path of destruction narrowed as the tornado moved to the outlying areas of the Double Creek Estates subdivision. Here the destruction became random. Figure 14 shows a mobile home that sustained only minor damage, while a short distance away a large tree was uprooted and another house lost half of its roof. The tornado then moved across CR 309 and ended in a heavily wooded area southwest of Jarrell.

Figure 11. Close-up view of a typical slab-on-grade foundation of houses in the Double Creek Estates subdivision. Only one sill plate remains connected to the concrete foundation.

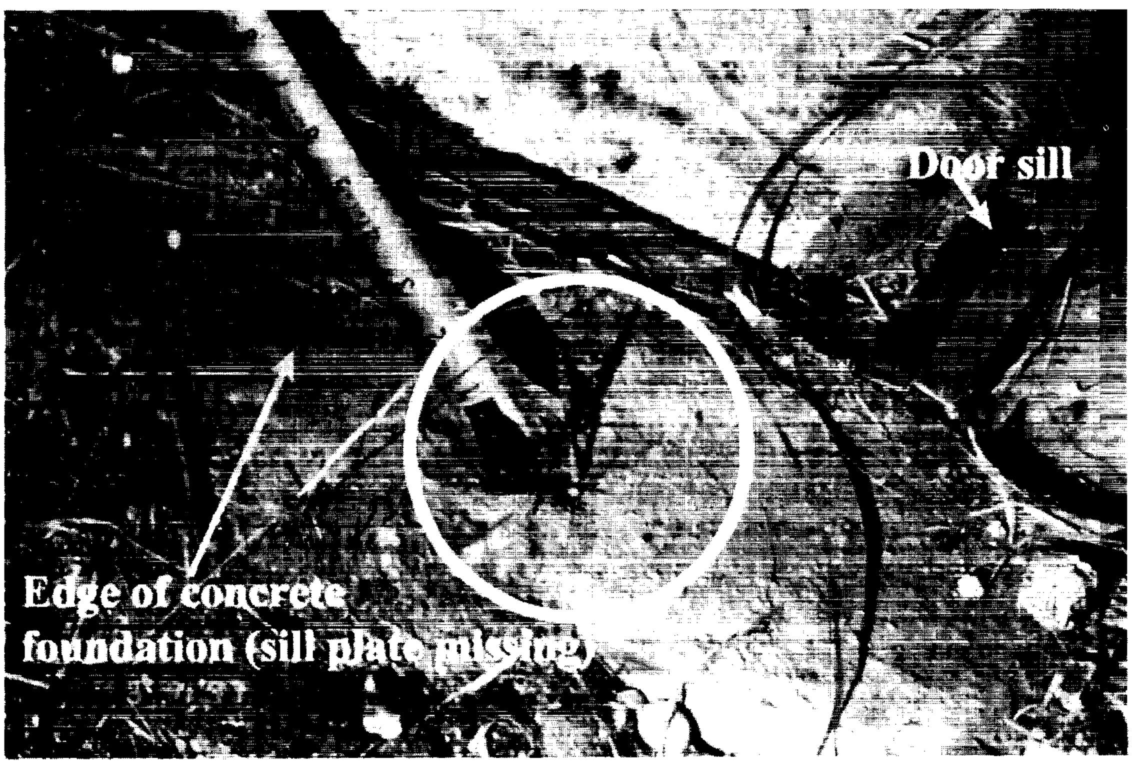

Figure 12. Evidence of nail that was used for connecting sill plate to concrete foundation.

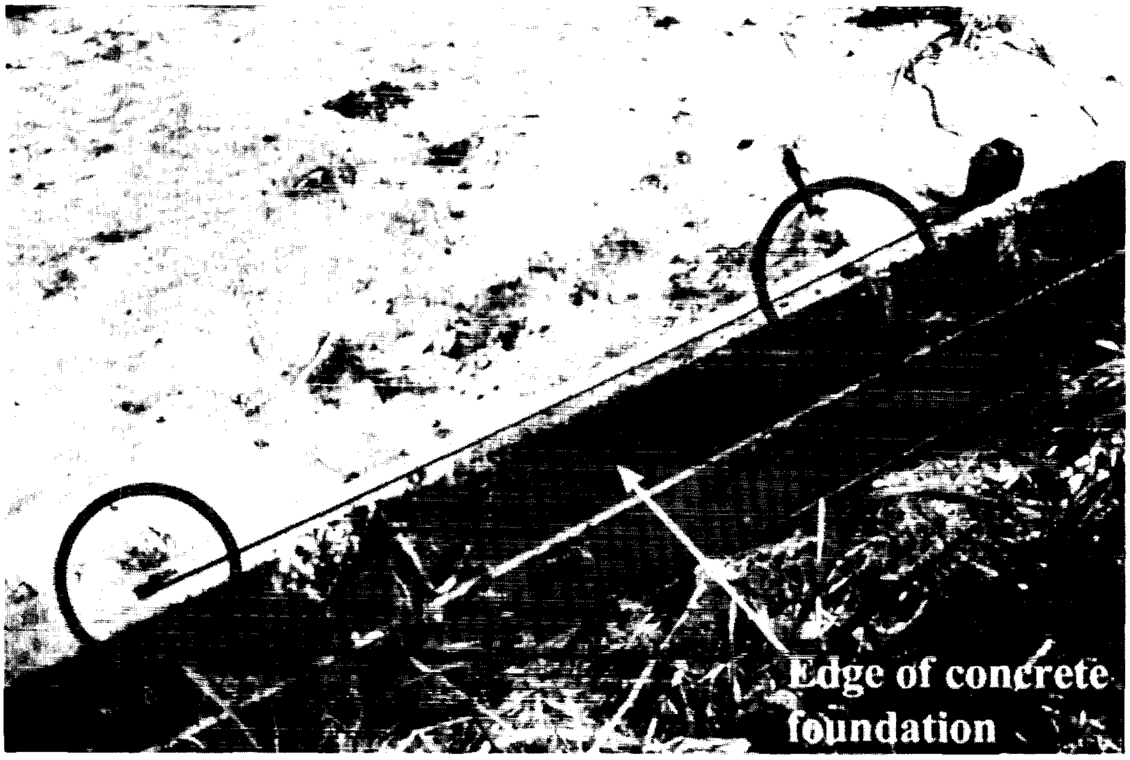

Figure 13. Evidence of pullout of nails used to fasten sill plates to concrete foundation.

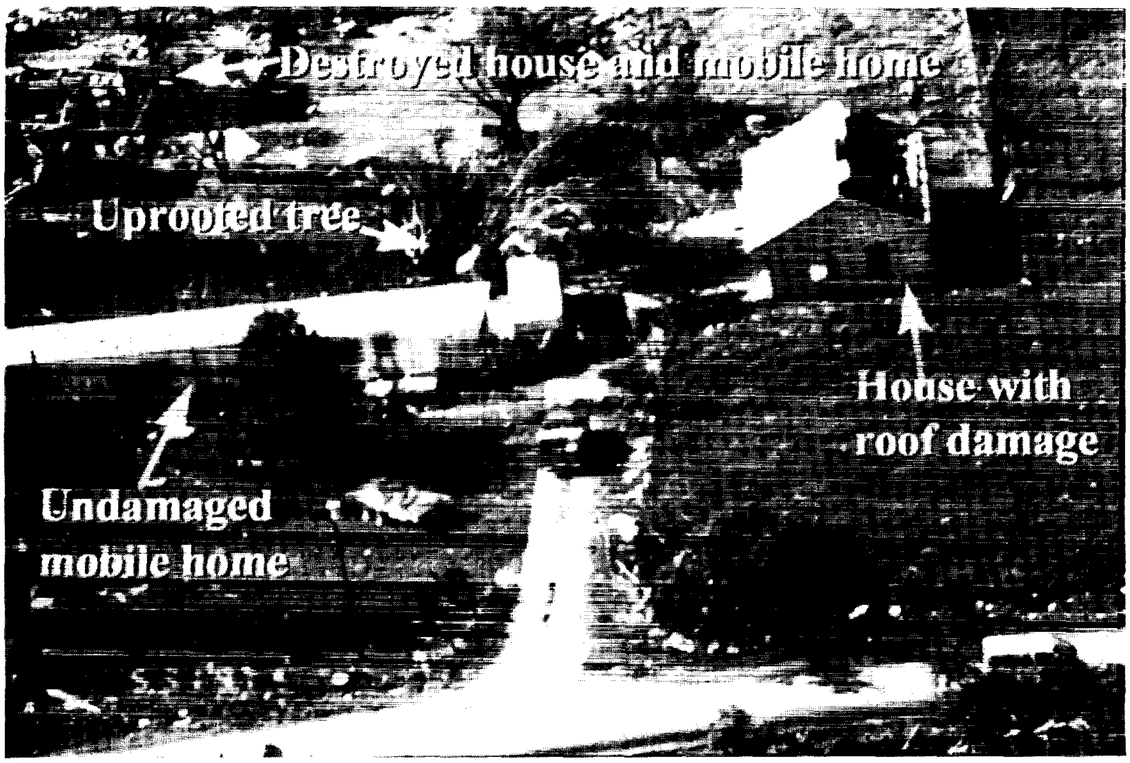

Figure 14. Structural damage near the end of the path of the Jarrel tornado.

3.3 Assessments of Maximum Intensity of the Jarrell Tornado

The Jarrell tornado offered an opportunity to assess subjective tornado intensity estimates obtained on the basis of damage descriptions defining the Fujita scale. Based on the damage description associated with F5 tornadoes in the Fujita intensity scale (see Appendix 1), NWS meteorologists estimated the Jarrell tornado to be a category F5 tornado (Alexander, 1997). We present an estimate of wind speeds in the Jarrell tornado based on structural engineering considerations, rather than on the relation between damage description and wind speeds currently postulated in the Fujita intensity scale.

The basic design wind speed specified in the ASCE 7-95 Standard (1995) for the design of buildings in Central Texas is 40 m/s (90 mph). Design and construction practices for residential structures such as those destroyed by the Jarrell tornado are normally not based on formal engineering calculations but, rather, on experience and judgment. When they are sound -- which in the absence of stringent inspection and quality control is not always the case -- such practices are commensurate with the requirement that buildings should be capable of withstanding wind speeds higher than the basic design wind speed, implying an overall safety margin with respect to loading of at most 1.5 to 2. Assume that in areas with a 40 m/s (90 mph) basic design wind speed, buildings are capable of resisting wind induced loads twice as large as the loads induced by the 40 m/s (90 mph) speed. It then follows from the proportionality of the wind loads to the square of the wind speeds that those buildings would be expected to collapse under wind speeds in excess of $40 \times (2)^{1/2} = 56.6$ m/s (125 mph). The expectation would be even stronger that wind speeds corresponding to wind 3 times as large as those induced by the 40 m/s speed (i.e., 69.2 m/s (155 mph) wind speeds) would leave no buildings standing, especially if the construction is mediocre or poor, as appears to have been the case for buildings destroyed by the Jarrell tornado.

Speeds assigned to F3 tornadoes in the Fujita classification are about 72 m/s to 94 m/s (158 mph to 206 mph). For a building in Central Texas to resist such speeds, its safety margin with respect to wind loads would have to be about 3.1 to 5.5. There is no reason to believe that any of the structures destroyed by the Jarrell tornado were that strong. We note that 90 m/s (201 mph) wind speeds, which in the Fujita classification are associated with F3 tornadoes, would likely utterly destroy most residential homes not only in a 40 m/s (90 mph) basic design wind speed zone, but also in hurricane-prone areas with 63 m/s (140 mph) basic design wind speeds. On the basis of the information presented in this report we conclude that the strongest damage caused by the Jarrell tornado can be explained by wind speeds corresponding to an F3 rating on the Fujita tornado intensity scale. Our conclusion, first conveyed by the authors to NOAA in June 1997, is consistent with an independent assessment by Texas Tech University (Mehta, 1997), that was also based on observations of damage and structural engineering considerations.

4. Conclusions and Recommendations

Our conclusions are:

(1) The strongest damage caused by the Jarrell tornado can be explained by wind speeds corresponding to an F3 rating (i.e., 71 m/s to 92 m/s). An F4 rating, or the F5 rating officially

issued by NWS, need not be assumed to explain the observed damage.

(2) The Fujita tornado intensity scale has two major shortcomings that can lead to misclassification of tornadoes by non-engineers:

(a) It does not reflect the dependence of the tornado wind speeds causing various types of damage upon the design wind speed specified for the zone of interest. For example, a tornado wind speed that tears down the roofs of well constructed houses may be assumed to be larger by a factor of roughly 1.6 for zones in which the design wind speed is 63 m/s than for zones where the design wind speed is 40 m/s; that is, damage that in a 63 m/s zone could be attributed to an F5 tornado could be explained in a 40 m/s zone by F3 tornado winds.

(b) The damage descriptions include the terms "well-constructed houses" and "strong frame houses." Non-engineers normally cannot be expected to have the requisite technical knowledge needed for ascertaining whether or not houses destroyed by tornadoes were well-constructed or strong.

These conclusions are of significance insofar as:

(1) Tornado misclassification corrupts the database used to design criteria for structures whose performance must be unaffected by strong tornadoes.

(2) Since, as pointed out earlier, even an F3 tornado could flatten most residential buildings, NWS should in our opinion consider revising its safety recommendations, which are based on the assumption that almost all tornadoes, including F4 events, are survivable.

(3) Ascribing failures to unrealistically high wind speeds when the actual speeds are in fact lower discourages the application and enforcement of standards, such as ASCE 7, that are capable of reducing loss of life and property caused by most tornadoes.

(4) A stronger contribution of the structural engineering profession to efforts aimed at assessing tornado wind speeds could help improve the knowledge needed to protect the public from tornado-induced losses.

For these reasons we recommend that:

(1) Engineers, meteorologists, disaster relief workers, and representatives of standards organizations, regulatory bodies, and the insurance industry should work together to develop a tornado intensity classification scale wherein damage descriptions make specific reference to basic design wind speeds and to quality of construction as defined by degree of conformity to standards requirements. As a basis for discussion, we suggest that wind speed ranges included in tornado intensity classifications be affected by numerical factors related to the basic design wind speeds and to quality of construction. Factors related to quality of

construction could be specified in accordance with matrices of the type considered for development by insurance companies, wherein conformity to various standards requirements is estimated both qualitatively and quantitatively.

(2) ASCE, in collaboration with other interested parties, should consider organizing and training local ASCE chapter volunteer engineering teams that could join in expeditiously with local NOAA and other specialized personnel, and promptly record from the strength of their professional knowledge significant evidence on tornado intensities. This recommendation is based on experience which shows that evidence of tornado effects is often removed from the site less than a day after a tornado occurrence, that is, *before* survey teams can reach the site.

(3) The documentation for the approximately 150 tornadoes (about 0.5% of the total number of recorded tornadoes in the United States) that were classified as F5 should be revisited in an attempt to reassess their classification. Such reassessment would involve a relatively small effort and would, even if only partly successful, allow some updating of the database from which probability distributions of tornado wind speeds have been estimated so far. This recommendation follows a proposal by K. Mehta of Texas Tech University.

(4) Continuing efforts to develop procedures for obtaining direct, scientific tornado wind speed measurements should be encouraged. On the one hand such measurements would add valuable data to the database, even though the effect of such addition to the more than 25,000 data currently available would be small: many years of data would have to be collected for that effect to be significant. On the other hand, scientific measurements can help to assess estimates of tornado wind speeds based on observations of damage. This would in turn help to effect corrections to the existing database by allowing the use of Bayesian or other updating techniques.

5. References

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6. Acknowledgments

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Appendix 1 -- **Fujita Tornado Intensity Scale** [1]

Category	**Definition -- Effects**
F0	Gale tornado (Approximate wind speeds 18-32 m/s (40-72 mph)): Light damage. Some damage to chimneys; break branches off trees; push over shallow rooted trees; damage sign boards.
F1	Moderate tornado (Approximate wind speeds 33-50 m/s (73-112 mph)): Moderate damage. The lower limit is the beginning of hurricane wind speed; peel surface off roofs; mobile homes pushed off foundations or overturned; moving autos pushed off the roads.
F2	Significant tornado (Approximate wind speeds 51-70 m/s (113-157 mph)): Considerable damage. Roofs torn off frame houses; mobile homes demolished; boxcars pushed over; large trees snapped or uprooted; light-object missiles generated.
F3	Severe tornado (Approximate wind speeds 71-92 m/s (158-206 mph)): Severe damage. Roofs and some walls torn off well-constructed houses; trains overturned; most trees in forests uprooted; heavy cars lifted off ground and thrown.
F4	Devastating tornado (Approximate wind speeds 93-116 m/s (207-260 mph)): Devastating damage. Well constructed houses leveled; structures with weak foundation blown off some distance; cars thrown and large missiles generated.
F5	Incredible tornado (Approximate wind speeds 117-142 m/s (261-318 mph)): Incredible damage. Strong frame houses lifted off foundations and carried considerable distance to disintegrate; automobile-sized missiles fly through the air in excess of 100 yards; trees debarked; incredible phenomena will occur.

[1] Excerpted from National Post-storm Data Acquisition Plan, Federal Coordinator for Meteorological Services and Supporting Research, National Oceanic and Atmospheric Administration, Silver Spring, March 1995.